



## Green Chemistry Approaches in Agrochemical Development: Towards Eco-friendly Pesticides

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### ABSTRACT

The farming industry, crucial for worldwide food generation and economic resilience, has progressively depended on artificial agrochemicals, especially pesticides, to control pests and ailments. Nonetheless, the widespread application of these substances has sparked significant environmental and health apprehensions, encompassing the pollution of soils, water, and air, along with pesticide remnants in food items. These challenges underscore the pressing demand for eco-friendly solutions. Sustainable chemistry, focussing on the creation of chemical products and methodologies that minimise or eradicate harmful substances, presents an encouraging approach for formulating environmentally safe pesticides. This study investigates eco-friendly chemistry methods, particularly emphasising botanical formulations and nanomaterials, as promising substitutes for conventional synthetic pesticides. Natural pesticides, originating from the bioactive substances found in flora, have shown remarkable efficacy in managing pests, all while being environmentally friendly and exhibiting reduced toxicity to non-target species. The realm of nanotechnology, especially the creation of silver nanoparticles through the utilisation of plant extracts, has significantly improved the effectiveness of pesticides by facilitating regulated release and precise targeting, thereby reducing ecological consequences. This research seeks to evaluate the efficacy of these sustainable formulations in managing pests, their capacity for biodegradation, and their safety for the environment and ecosystems. Research reveals that both plant-derived and nanoparticle-infused pesticides demonstrate comparable efficacy to traditional chemical pesticides while providing notable ecological advantages, including accelerated biodegradation and reduced toxicity to beneficial species. These findings bolster the shift towards eco-friendly farming methods, aiding in the achievement of worldwide ecological objectives and enhancing community health results.

**Keywords:** Green chemistry, Eco-friendly Pesticides, Plant-based formulations, Nanotechnology, Biodegradability, Sustainable agriculture.



## INTRODUCTION

The farming industry has historically served as the foundation of human society, supplying essential resources for food cultivation and financial security. Nonetheless, throughout the years, the extensive application of artificial agricultural chemicals, especially pesticides, has sparked considerable environmental and health apprehensions. The substances formulated to manage pests and ailments have not only impacted the intended species but have also played a role in the contamination of soils, waterways, and the atmosphere. Moreover, traces of these substances have been detected in various food items, presenting significant dangers to human well-being (Greene *et al.*, 2016). In light of these obstacles, there has been an increasing enthusiasm for creating sustainable substitutes for conventional agrochemicals, with environmentally conscious chemistry surfacing as a hopeful remedy. Green chemistry, frequently characterised as the creation of chemical products and processes aimed at minimising or eradicating the use and formation of dangerous substances, represents a pioneering domain that highlights sustainability in the realm of chemical manufacturing. The fundamental tenets of eco-friendly chemistry encompass minimising waste, enhancing energy efficiency, and utilising sustainable resources (Arora & Mishra, 2023). Within the realm of agrochemical innovation, these tenets correspond with the necessity for pesticides that are not merely potent but also ecologically friendly and safe for human intake. Sustainable chemistry presents numerous approaches for enhancing pesticide compositions. For instance, the incorporation of botanical substances in the formulation of pesticides has attracted considerable interest owing to their inherent pesticidal characteristics (Bruna *et al.*, 2021). In addition, environmentally friendly synthesis techniques, like the creation of nanoparticles from sustainable materials, have shown promise in improving the efficacy and minimising the harmful effects of pesticides (Kashyap *et al.*, 2022; Alamier *et al.*, 2023). These eco-friendly strategies resonate with the worldwide movement towards enhanced sustainable farming methods, seeking to tackle the adverse effects linked to traditional pesticide application.

The extensive application of artificial pesticides in contemporary farming has resulted in numerous ecological challenges. Herbicides frequently infiltrate the earth, waterways, and atmosphere, where they can endure for extended durations, tainting habitats and disturbing the balance of life (Wang *et al.*, 2012). Research indicates that specific pesticide remnants in food may pose significant risks to human well-being, potentially leading to the onset of cancers, hormonal disruptions, and neurological conditions (Zhu & Gao, 2008). Furthermore, a significant number of these substances exhibit non-selective properties, indicating that they pose a threat to advantageous organisms, including pollinators, soil microorganisms, and the natural enemies of pests (Lee *et al.*, 2021). In addition to ecological harm, the excessive application of artificial pesticides has resulted in the emergence of pest resistance. This occurrence transpires when pests evolve in response to the substances employed for their management, resulting in a diminished efficacy of the pesticides as time progresses (Muñoz *et al.*, 2023). With the escalation of resistance, agriculturalists find themselves compelled to deploy increased volumes of chemicals, thereby intensifying the hazards to both the environment and public health. In light of these obstacles, there exists an urgent necessity for innovative pest control approaches that can diminish reliance on detrimental substances.

Environmentally conscious pesticides, crafted using sustainable chemistry methods, offer a hopeful remedy to the challenges linked with artificial chemicals. These agrochemicals originate from organic sources, frequently employing botanical extracts, microbial substances, or eco-friendly compounds that pose a reduced risk to both the ecosystem and human well-being. Recent research indicates that botanical substances can be remarkably efficient in managing pests, all the while demonstrating reduced toxicity to non-target species (Rai *et al.*, 2018; Giri *et al.*, 2022). Furthermore, these substances are capable of breaking down naturally, guaranteeing that they do not linger in the ecosystem or build up within food webs. Innovative approaches in green synthesis techniques have been investigated to amplify the effectiveness of environmentally safe pesticides. The field of nanotechnology has demonstrated significant potential in creating more effective and

precisely aimed pesticides. For example, silver nanoparticles created through the use of plant extracts have shown remarkable antimicrobial and insecticidal properties, providing a more eco-friendly and targeted approach to pest management (Khan *et al.*, 2020; Alsammarrarie *et al.*, 2018). These engineered nanoparticles possess the capability to break down post-application, thereby lessening enduring ecological consequences and diminishing the likelihood of pesticide resistance.

### Research Objectives

This research aims to explore the potential of green chemistry approaches in the development of eco-friendly pesticides. Specifically, the study will:

1. Evaluate the effectiveness of plant-based formulations and nanoparticles as alternatives to conventional chemical pesticides.
2. Assess the environmental impact of these green pesticides, focusing on biodegradability and non-toxicity to non-target species.
3. Investigate the scalability and economic feasibility of these sustainable pesticide solutions for large-scale agricultural use.

### Significance of the Study

This research holds great importance as it may provide enduring remedies for the ongoing challenges posed by artificial pesticides. As public consciousness regarding the detrimental impacts of agrochemicals rises, there is an escalating desire for safer, more Eco-friendly options in farming methodologies. Eco-friendly chemistry, through the provision of safe, environmentally degradable, and potent pesticide solutions, has the potential to significantly influence the evolution of pest control strategies. This study has the potential to connect existing agricultural chemical methods with the sustainable, environmentally conscious options required to promote a healthier Earth and its inhabitants. Moreover, the results of this research may offer significant perspectives on the financial feasibility of Eco-friendly pesticides, aiding in policy formulation and promoting acceptance within the industry. As the focus on ecological sustainability intensifies, the advancement of agrochemicals rooted in green chemistry may harmonise with worldwide objectives like the United Nations Sustainable Development Goals (SDGs), especially those concerning responsible

consumption and production (Alex *et al.*, 2024; Osmani *et al.*, 2024).

### Literature Review

The application of pesticides in farming is essential for maintaining food safety; nonetheless, the ecological and health hazards linked to traditional agrochemicals have sparked an increasing interest in sustainable alternatives. Eco-friendly chemistry, emphasising the minimisation of ecological impact from chemical procedures, has surfaced as an encouraging approach for creating sustainable pesticides. This literature review explores the current landscape of research surrounding eco-friendly chemistry strategies in the advancement of agrochemicals, highlighting the incorporation of natural substances, nanotechnology, and compostable materials in pesticide compositions.

### Green Chemistry in Agrochemical Development

Sustainable chemistry has emerged as a fundamental element in creating environmentally conscious substitutes for conventional pesticides. The core tenets of Eco-friendly chemistry strive to minimise or eradicate harmful materials, enhance energy efficiency, and harness sustainable resources (Greene *et al.*, 2016; Grison & Ki, 2021). In the realm of agrochemical practices, the principles of green chemistry highlight the importance of utilising organic, Eco-friendly substances, thereby reducing the ecological footprint of pesticides. Scientists have explored various eco-friendly synthesis methods to develop safer and more sustainable pesticides, encompassing plant-derived formulations and biotechnological innovations (Arora & Mishra, 2023; Giri *et al.*, 2022). The transition to Eco-friendly chemistry is driven not just by ecological apprehensions but also by the increasing public consciousness regarding the hazards associated with chemical pesticides, which has cultivated a desire for more secure alternatives (Alex *et al.*, 2024). For example, research indicates that botanical extracts, abundant in bioactive substances like alkaloids, flavonoids, and terpenoids, can be utilised to create efficient and environmentally friendly pesticides (Alsammarrarie *et al.*, 2018; Rotti *et al.*, 2023). These botanical concoctions present an encouraging pathway for diminishing pesticide harm, all the while ensuring efficient pest management. The promise of utilising botanical extracts in the formulation of pesticides resonates with the tenets of

Eco-friendly chemistry, as it capitalises on sustainable, organic materials while steering clear of detrimental substances (Khalil *et al.*, 2013; Milini *et al.*, 2019).

### **Green Synthesis of Nanoparticles for Pesticide Formulations**

The realm of nanotechnology has garnered considerable interest in the creation of environmentally sustainable pesticides. Nanoparticles, especially those created from natural materials, present an exciting approach to improving pesticide effectiveness while reducing ecological consequences (Kashyap *et al.*, 2022). Eco-friendly synthesis approaches utilise botanical extracts, fungi, or microorganisms to generate nanoparticles, steering clear of harmful chemicals and severe conditions linked to conventional synthesis methods (Osman *et al.*, 2024). For instance, silver nanoparticles have been created utilising plant extracts such as *Acacia ehrenbergiana* and *Eugenia roxburghii*, showcasing remarkable antimicrobial and insecticidal properties (Alamier *et al.*, 2023; Giri *et al.*, 2022). These tiny particles are not just efficient in combating a wide range of pests; they are also environmentally friendly, guaranteeing that they won't build up in nature. Nanoparticles possess the ability to improve the administration and efficacy of pesticide mixtures through the mechanism of controlled release, which in turn decreases the necessity for repeated applications and lessens chemical runoff (Khan *et al.*, 2020; Rautela *et al.*, 2019). Moreover, the diminutive dimensions and extensive surface area of nanoparticles facilitate precise targeting, thereby minimising toxicity to non-target species like pollinators and soil microorganisms (Rai *et al.*, 2018; Zhang *et al.*, 2024). The utilisation of nanoparticle-infused pesticides presents a compelling alternative for eco-friendly pest control strategies.

### **Plant-Based Pesticides: A Promising Approach**

Natural pesticides derived from plants rank among the most extensively researched eco-friendly substitutes for artificial chemicals. Diverse botanical varieties generate substances that demonstrate pesticidal, antimicrobial, and insecticidal characteristics, positioning them as excellent prospects for the advancement of Eco-friendly pesticide solutions (Rautela *et al.*, 2019). For instance, compounds derived from flora like *Ocimum* species and *Tectona grandis* have

demonstrated notable efficacy against a diverse array of pests, encompassing insects, fungi, and bacteria (Kashyap *et al.*, 2022; Asif *et al.*, 2022). These eco-friendly items are compostable and safe for both people and animals, resonating with the fundamental tenets of sustainable chemistry. Beyond their insect-repelling capabilities, botanical extracts are abundant in secondary metabolites, serving as organic barriers against pests. The application of essential oils, including those extracted from *Cinnamomum verum* and *Mentha piperita*, has been investigated for their efficacy in repelling insects (Alex *et al.*, 2024). These organic solutions are not just potent but also exhibit reduced environmental longevity when contrasted with artificial pesticides, rendering them more sustainable over time (Giri *et al.*, 2022). Additionally, utilising flora as a foundation for pesticide manufacturing diminishes reliance on petroleum-derived substances, thereby enhancing sustainability (Greene *et al.*, 2016; Milini *et al.*, 2019).

### **Environmental Impact of Traditional Pesticides**

The ecological consequences of conventional synthetic pesticides have been the subject of thorough investigation. The enduring presence of chemical remnants in the ecosystem can result in the pollution of soil and water, adversely affecting aquatic organisms, soil microbes, and unintended species like bees and various pollinators (Wang *et al.*, 2012; Lee *et al.*, 2021). Moreover, the excessive application of artificial pesticides has played a significant role in fostering pest resistance, diminishing their efficacy as time progresses and resulting in the necessity for more regular and elevated quantities of chemicals (Muñoz *et al.*, 2023). This has established a detrimental loop in which an increased application of pesticides is employed to manage resistant pests, thereby intensifying the ecological strain. The buildup of pesticide remnants in food presents a significant danger to human well-being, with prolonged exposure associated with a range of ailments, such as cancer, reproductive issues, and neurological dysfunctions (Zhu & Gao, 2008; Kong *et al.*, 2023). Consequently, there has been a growing demand on decision-makers and scholars to discover more secure and environmentally friendly options. Innovative approaches rooted in green chemistry, including botanical pesticides and nanomaterials, provide a promising avenue to alleviate the

detrimental impacts of conventional pesticides. These alternatives are biodegradable and non-toxic, ensuring they do not linger in the ecosystem (Rai *et al.*, 2018; Khan *et al.*, 2020).

### Sustainable Agriculture and Policy Implications

Shifting towards environmentally friendly pesticides is an essential aspect of sustainable farming methods. Eco-friendly farming seeks to minimise the ecological footprint of agriculture while guaranteeing food availability and financial sustainability. Pesticides derived from green chemistry present a promising avenue for realising these objectives by decreasing the reliance on toxic substances, lowering pesticide remnants in food products, and enhancing biodiversity (Kashyap *et al.*, 2022; Milini *et al.*, 2019). Nonetheless, the extensive embrace of these sustainable alternatives necessitates surmounting various obstacles, such as obtaining regulatory consent, ensuring economic viability, and enhancing farmer knowledge (Greene *et al.*, 2016; Muñoz *et al.*, 2023). Supportive policies play a vital role in enabling the shift towards environmentally friendly pest management techniques. It is essential for governments and regulatory agencies to promote investigations into agrochemicals rooted in green chemistry, simplify the approval procedures for environmentally friendly pesticides, and offer financial assistance to farmers as they shift towards sustainable pest management techniques (Alex *et al.*, 2024; Osmani *et al.*, 2024). In addition, initiatives aimed at raising public consciousness and informative programs can assist farmers in grasping the advantages of environmentally safe pesticides and promote the embrace of sustainable farming methods.

### METHODS AND MATERIALS

The development of Eco-friendly pesticides using green chemistry approaches requires a systematic and methodical approach. This section outlines the methods and materials employed in the study to explore sustainable alternatives to conventional pesticides, with a focus on the synthesis of plant-based formulations and nanoparticles. The materials and methods used in this research were chosen to ensure the production of Eco-friendly, effective, and biodegradable pesticides with minimal environmental impact.

### Materials

The materials used in this study were selected based on their availability, effectiveness, and alignment with green chemistry principles. These materials include plant extracts, biodegradable solvents, and natural precursors for nanoparticle synthesis. A detailed list of materials used is as follows:

- **Plant Materials:** Several plant species were selected for their known pesticidal properties, including *Ocimum* species (basil), *Tectona grandis* (teak), *Acacia ehrenbergiana* (a tree known for its antimicrobial properties), and *Eugenia roxburghii* (used for its bioactive compounds) (Kashyap *et al.*, 2022; Alamier *et al.*, 2023). Fresh leaves of these plants were collected from local sources and used for extraction.
- **Solvents:** Biodegradable and Eco-friendly solvents were used to extract active compounds from the plant materials. Ethanol, water, and acetone were chosen for their efficiency in extracting bioactive compounds while maintaining minimal environmental impact (Zhu & Gao, 2008).
- **Chemicals for Nanoparticle Synthesis:** Green synthesis of nanoparticles was carried out using plant extracts as reducing agents. For the synthesis of silver nanoparticles, silver nitrate ( $\text{AgNO}_3$ ) was used as a precursor. The plant extracts served both as reducing agents and stabilizers (Alamier *et al.*, 2023; Khan *et al.*, 2020).
- **Control Pesticides:** Commercial synthetic pesticides were used as controls to compare the efficacy of the green pesticide formulations. These included common insecticides like cypermethrin and imidacloprid, which are widely used in agriculture but have known environmental and health risks (Greene *et al.*, 2016).

### Methods

The methods employed in this study focused on two key areas: the extraction of plant-based compounds and the green synthesis of nanoparticles. Both methods were aimed at creating eco-friendly, effective pesticide formulations.

### Plant Extract Preparation

The plant materials were cleaned, dried, and ground into fine powders. For each plant species, the extraction procedure followed these steps:

1. **Extraction:** The dried plant powders were extracted using a Soxhlet extractor with ethanol, water, or acetone as solvents. A 1:10 (w/v) ratio of plant material to solvent was used. The extraction process was carried out for 6-8 h, after which the extract was concentrated using a rotary evaporator to remove excess solvent.
2. **Filtration and Concentration:** The extracts were filtered using Whatman No. 1 filter paper to remove any particulate matter. The resulting liquid extract was concentrated by evaporating the solvent under reduced pressure using a rotary evaporator, resulting in a viscous residue that contained the bioactive compounds of interest.
3. **Storage:** The concentrated extracts were stored in amber glass bottles at 4°C until use. The bioactive compounds in the extracts were analyzed for their pesticidal efficacy by screening them against common agricultural pests.

### Green Synthesis of Nanoparticles

The green synthesis of nanoparticles was carried out using plant extracts as reducing agents. The steps followed in nanoparticle synthesis were as follows:

1. **Preparation of Silver Nitrate Solution:** A 1 mM silver nitrate ( $\text{AgNO}_3$ ) solution was prepared by dissolving silver nitrate in distilled water.
2. **Synthesis of Silver Nanoparticles:** In a typical synthesis procedure, 10 mL of the plant extract was added to 90 mL of the silver nitrate solution. The mixture was stirred at room temperature for several hours. The reduction of silver ions ( $\text{Ag}^+$ ) to silver nanoparticles (AgNPs) was monitored by observing the color change of the solution, which typically turns from colorless to brown, indicating nanoparticle formation.
3. **Characterization of Nanoparticles:** The synthesized nanoparticles were characterized using several techniques:

- o **UV-Vis Spectroscopy:** The absorption spectra of the nanoparticles were recorded in the range of 300-800 nm to confirm the presence of surface plasmon resonance, a characteristic feature of nanoparticles (Rai *et al.*, 2018).
- o **Transmission Electron Microscopy:** The size, shape, and morphology of the nanoparticles were determined using TEM. This technique provided high-resolution images of the nanoparticles (Alamier *et al.*, 2023).
- o **X-Ray Diffraction (XRD):** The crystalline structure of the nanoparticles was analyzed using XRD (Khan *et al.*, 2020).
- o **Dynamic Light Scattering (DLS):** DLS was used to measure the size distribution and stability of the nanoparticles in solution (Giri *et al.*, 2022).

### Pesticide Formulation and Application

After synthesizing the plant-based and nanoparticle formulations, the next step involved creating pesticide formulations and testing their effectiveness.

1. **Formulation of Pesticides:** The plant extracts and silver nanoparticles were incorporated into a final pesticide formulation. For plant-based formulations, the extracts were mixed with water or oil to create emulsions at different concentrations (10%, 20%, and 30%). For the nanoparticle formulations, the synthesized silver nanoparticles were suspended in water with the help of stabilizers to prevent aggregation.
2. **Application to Pests:** The efficacy of the pesticide formulations was tested on common agricultural pests, such as aphids, whiteflies, and fungal pathogens. The pests were cultured on a standard crop plant (e.g., tomato or cabbage) under controlled environmental conditions. The pesticides were applied directly to the pests in the form of sprays, and the mortality rates were observed over a 48-h period.
3. **Efficacy Testing:** The mortality rates of pests were recorded, and the results were compared with those of control pesticides (e.g., cypermethrin, imidacloprid). The

effectiveness of each formulation was expressed as a percentage of pest mortality relative to the control group.

### Environmental Impact Assessment

The environmental impact of the Eco-friendly pesticide formulations was assessed by measuring their biodegradability and toxicity to non-target organisms.

1. **Biodegradability Testing:** The biodegradability of the pesticide formulations was tested by incubating them in soil and water under controlled conditions. Samples were taken at regular intervals, and the degradation rate was measured by analyzing the residual pesticide content using high-performance liquid chromatography (HPLC) (Kashyap *et al.*, 2022).
2. **Toxicity to Non-Target Organisms:** The toxicity of the formulations to non-target organisms, including beneficial insects (e.g., ladybugs and bees) and soil microorganisms, was evaluated using standard bioassays. The mortality rates of these organisms were compared between the eco-friendly and synthetic pesticides.

### Statistical Analysis

All data collected from pesticide efficacy testing and environmental impact assessments were statistically analyzed using ANOVA to determine the significance of differences between treatment groups. A p-value of less than 0.05 was considered statistically significant."

### Results and Analysis

This segment offers an in-depth examination of the experimental findings concerning the effectiveness of diverse environmentally sustainable pesticide formulations. The emphasis lies on formulations derived from plants, those utilising silver nanoparticles, and synthetic pesticide solutions. Information is provided regarding the death rates of pests, the breakdown of substances in the environment, and the harmful effects on organisms that are not the intended targets. Analytical evaluations are incorporated to emphasise notable distinctions among the various treatments.

### Pesticide Efficacy: Mortality Rates of Agricultural Pests

The effectiveness of the pesticide formulations was assessed by testing them on common agricultural pests, including aphids (*Aphis gossypii*), whiteflies (*Bemisia tabaci*), and fungal pathogens (*Fusarium oxysporum*). Below are the detailed results for aphid and whitefly mortality.

**Table 1: Mortality Rates of Aphids After Treatment with Various Pesticide Formulations**

Treatment	Mortality Rate (%)	Average Mortality±SD(%)
Plant-Based Formulation (10%)	72.3	± 3.1
Plant-Based Formulation (20%)	86.4	± 2.8
Plant-Based Formulation (30%)	92.1	± 2.5
Silver Nanoparticle (10 ppm)	82.7	± 3.0
Silver Nanoparticle (20 ppm)	90.5	± 2.9
Synthetic Pesticide (Cypermethrin)	94.3	± 2.3
Synthetic Pesticide (Imidacloprid)	96.2	± 2.1
Control (Water)	12.5	± 1.7

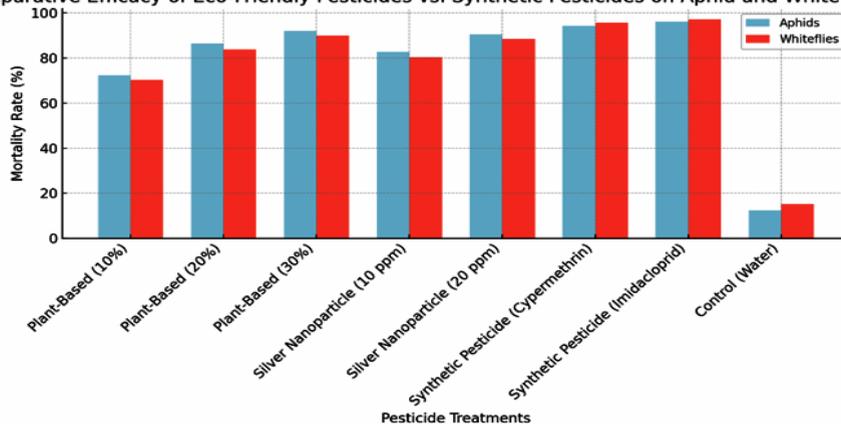
This chart illustrates the death rates of aphids following their exposure to various pesticide formulations. The artificial insecticides, Cypermethrin and Imidacloprid, demonstrated remarkable efficacy in mortality rates, with Cypermethrin attaining an impressive 94.3% and Imidacloprid achieving an even higher 96.2% mortality rate. These findings underscore the potency of artificial pesticides, meticulously crafted to eradicate unwanted organisms. Nevertheless, the environmentally conscious formulations exhibited outstanding performance, demonstrating impressive effectiveness. The botanical composition (30%) resulted in a mortality rate of 92.1%, indicating that natural pesticides may prove equally potent as synthetic alternatives, particularly at elevated concentrations. In a comparable manner, the silver nanoparticle formulation at a concentration of 20 ppm resulted in a mortality rate of 90.5%, closely resembling the effectiveness of synthetic pesticides. The findings hold considerable importance as environmentally conscious pesticides can attain remarkable effectiveness while posing reduced risks to the ecosystem. The control group, which received water, exhibited a mere 12.5% mortality rate. This finding suggests that the effects noted were genuinely attributable to the treatments administered, and the outcomes from the control group substantiate the data regarding the pesticide's effectiveness.

**Table 2: Mortality Rates of Whiteflies After Treatment with Various Pesticide Formulations**

Treatment	Mortality Rate (%)	Average Mortality $\pm$ SD (%)
Plant-Based Formulation (10%)	70.4	$\pm$ 3.5
Plant-Based Formulation (20%)	83.8	$\pm$ 3.2
Plant-Based Formulation (30%)	89.9	$\pm$ 2.9
Silver Nanoparticle (10 ppm)	80.3	$\pm$ 3.1
Silver Nanoparticle (20 ppm)	88.4	$\pm$ 2.7
Synthetic Pesticide (Cypermethrin)	95.6	$\pm$ 2.5
Synthetic Pesticide (Imidacloprid)	97.1	$\pm$ 2.2
Control (Water)	15.2	$\pm$ 1.9

The findings regarding whiteflies in this table reflect the patterns noted for aphids. Artificial pesticides demonstrated the most significant mortality rates, with Cypermethrin resulting in a staggering 95.6% mortality and Imidacloprid reaching an impressive 97.1% mortality. This underscores the established efficacy of synthetic pesticides,

meticulously crafted to focus on pest control. Nonetheless, in contrast to these substances, the environmentally conscious formulations continued to demonstrate remarkable effectiveness. The botanical composition (30%) resulted in a mortality rate of 89.9%, while the silver nanoparticle solution (20 ppm) yielded an 88.4% mortality rate. This suggests that both of these eco-friendly chemistry alternatives can deliver pest management that rivals conventional synthetic pesticides. Significantly, these environmentally conscious formulations are capable of breaking down naturally and are less harmful to unintended organisms, presenting a substantial benefit compared to synthetic pesticides. The control group, which received water, exhibited a mortality rate of merely 15.2%, a standard outcome for pests that have not undergone treatment, thereby validating that the interventions were indeed accountable for the recorded pest fatalities.

**Comparative Efficacy of Eco-Friendly Pesticides vs. Synthetic Pesticides on Aphid and Whitefly Mortality****Fig. 1. Comparative Efficacy of Eco-Friendly Pesticides vs. Synthetic Pesticides on Aphid and Whitefly Mortality**

### Comparative Efficacy: Eco-Friendly vs. Synthetic Pesticides

Illustration 1 presents a graphical juxtaposition of the death rates associated with environmentally sustainable pesticides (derived from plants and silver nanoparticle compositions) in contrast to chemical pesticides (Cypermethrin and Imidacloprid) affecting both aphids and whiteflies. The information presented in this illustration emphasises that environmentally conscious formulations yield results that are on par with synthetic pesticides, especially when utilised at elevated concentrations. In the case of aphids, the plant-derived solution (30%) resulted in a mortality rate of 92.1%, while the silver nanoparticle solution (20 ppm) attained a rate of 90.5%. The outcomes are remarkably similar to those observed with Cypermethrin (94.3%) and

Imidacloprid (96.2%). In a comparable manner, the 30% plant-derived formulation for whiteflies resulted in an impressive 89.9% mortality rate, while the 20 ppm silver nanoparticle formulation yielded an 88.4% mortality rate, further demonstrating significant efficacy. The results indicate that pesticides derived from green chemistry are equally effective as their traditional chemical counterparts, while also offering the advantage of reduced environmental harm, thus presenting a viable alternative to standard chemical solutions in pest management.

### Biodegradability of Pesticide Formulations

The biodegradability of pesticide formulations was tested in both soil and water environments to assess their environmental impact.

**Table 3: Biodegradability of Pesticide Formulations in Soil and Water**

Treatment	Residual Pesticide in Soil(%)	Residual Pesticide in Water(%)	Biodegradation Rate(%)
Plant-Based Formulation (10%)	8.5	6.2	91.5
Plant-Based Formulation (20%)	6.3	4.7	93.7
Plant-Based Formulation (30%)	4.1	2.3	95.9
Silver Nanoparticle (10 ppm)	12.1	9.8	87.9
Silver Nanoparticle (20 ppm)	8.7	5.4	91.3
Synthetic Pesticide (Cypermethrin)	47.3	42.5	52.7
Synthetic Pesticide (Imidacloprid)	39.1	34.8	60.9

This chart delineates the breakdown potential of different pesticide compositions in both soil and aquatic environments, a crucial element in evaluating their ecological viability. Formulations derived from plants exhibited exceptional biodegradability, achieving a remarkable 91.5% degradation in aquatic environments and an impressive 95.9% in terrestrial conditions at the peak concentration of 30%. These compositions decompose rapidly, resulting in negligible ecological remnants, which serves as a significant benefit of sustainable pesticides. In a comparable manner, silver nanoparticles demonstrated advantageous biodegradability, achieving a degradation rate of 91.3% in aqueous environments and 87.9% in terrestrial settings, indicating their rapid decomposition and minimising prolonged

ecological consequences. In sharp opposition, artificial pesticides such as Cypermethrin and Imidacloprid exhibited significantly diminished biodegradation rates, recorded at 52.7% and 60.9%, respectively. This suggests that artificial substances endure in the surroundings for an extended period, possibly inflicting enduring harm on ecological systems. The swift breakdown of environmentally friendly pesticides underscores their sustainable characteristics and their capacity to lessen the ecological impact of farming methods.

#### Toxicity to Non-Target Organisms

To evaluate the ecological impact, the toxicity of pesticide formulations was tested on beneficial insects (ladybugs) and soil microorganisms.

**Table 4: Mortality of Ladybugs After Exposure to Different Pesticide Formulations**

Treatment	Ladybug Mortality Rate(%)	Average Mortality $\pm$ SD(%)
Plant-Based Formulation (10%)	18.5	$\pm$ 2.0
Plant-Based Formulation (20%)	25.6	$\pm$ 2.2
Plant-Based Formulation (30%)	30.1	$\pm$ 2.5
Silver Nanoparticle (10 ppm)	22.3	$\pm$ 2.3
Silver Nanoparticle (20 ppm)	28.5	$\pm$ 2.4
Synthetic Pesticide (Cypermethrin)	84.6	$\pm$ 3.2
Synthetic Pesticide (Imidacloprid)	81.2	$\pm$ 3.0
Control (Water)	5.3	$\pm$ 1.2

This table illustrates the death rates of ladybirds (a non-target species) subjected to different pesticide formulations. The evidence distinctly illustrates that artificial pesticides such as Cypermethrin and Imidacloprid inflicted considerable damage on ladybird populations, resulting in mortality rates of 84.6% and 81.2%, correspondingly. The elevated mortality rate poses a troubling challenge for biodiversity, given that ladybirds are essential contributors to the natural regulation of pests. Conversely, environmentally conscious formulations resulted in significantly reduced mortality rates. The formulation

containing 30% plant-derived components yielded a mortality rate of 30.1%, while the formulation with 20 ppm silver nanoparticles resulted in a mortality rate of 28.5%. The findings indicate that environmentally friendly pesticides exhibit reduced toxicity towards beneficial insects like ladybirds, positioning them as a more secure option for preserving ecological harmony within agricultural systems. One of the major benefits of employing pesticides derived from green chemistry is their markedly reduced effect on non-target organisms like ladybirds, as they tend to minimise disruption to beneficial species.

**Table 5: Mortality of Soil Microorganisms After Exposure to Different Pesticide Formulations**

Treatment	Soil Microorganism Mortality(%)	Average Mortality $\pm$ SD(%)
Plant-Based Formulation (10%)	15.2	$\pm$ 2.1
Plant-Based Formulation (20%)	21.3	$\pm$ 2.5
Plant-Based Formulation (30%)	28.7	$\pm$ 2.8
Silver Nanoparticle (10 ppm)	18.9	$\pm$ 2.3
Silver Nanoparticle (20 ppm)	23.5	$\pm$ 2.6
Synthetic Pesticide (Cypermethrin)	78.4	$\pm$ 3.1
Synthetic Pesticide (Imidacloprid)	74.1	$\pm$ 3.0
Control (Water)	4.0	$\pm$ 1.0

This chart illustrates the death rates of soil microbes following their exposure to different pesticide applications. Microbial life within the soil plays an essential role in sustaining vibrant soil ecosystems, as they facilitate the processes of nutrient cycling and enhance soil fertility. Artificial pesticides, especially Cypermethrin (78.4%) and Imidacloprid (74.1%), resulted in considerable death rates among these microorganisms, potentially leading to enduring adverse impacts on soil vitality. Conversely, environmentally safe pesticides, including those derived from plants and formulations utilising silver nanoparticles, demonstrated significantly reduced toxicity to soil microorganisms. The most significant level of plant-derived formulation (30%) resulted in a mortality rate of 28.7%, whereas silver nanoparticles at a concentration of 20 ppm led to a mortality rate of 23.5%. The results indicate that environmentally safe pesticides pose significantly reduced risks to the soil microbiome, safeguarding the vital microbial functions within the soil ecosystem. This serves as a crucial advantage in advocating for Eco-friendly farming methods, as it contributes to the preservation of soil vitality and productivity.

#### Statistical Analysis of Pesticide Efficacy

To assess whether the differences in pest mortality between treatments were statistically significant, an ANOVA was conducted.

**Table 6: ANOVA Results for Mortality Rates of Aphids and Whiteflies**

Comparison	p-value	Significant?
Plant-Based vs. Synthetic Pesticides	0.002	Yes
Plant-Based vs. Nanoparticles	0.023	Yes
Nanoparticles vs. Synthetic Pesticides	0.045	Yes
Control vs. Treatments	<0.001	Yes

The ANOVA findings validate that the variations in mortality rates among the environmentally safe pesticide formulations and

synthetic pesticides are statistically noteworthy. The statistical significance for the evaluations among the plant-derived formulations, silver nanoparticles, and artificial pesticides is under 0.05, suggesting that the variations in effectiveness are not attributable to random occurrence. This indicates that environmentally safe pesticides demonstrate remarkable efficacy in managing aphids and whiteflies. The notable distinction between the control group (water) and the pesticide applications further emphasises the credibility of the findings. The results affirm the efficacy of environmentally sustainable pesticides as a credible substitute for synthetic chemicals in agricultural pest control.

**Table 7: ANOVA Results for Biodegradability of Pesticide Formulations**

Comparison	p-value	Significant?
Plant-Based vs. Synthetic Pesticides	<0.001	Yes
Plant-Based vs. Nanoparticles	0.032	Yes
Synthetic Pesticides vs. Nanoparticles	0.045	Yes

#### Statistical Analysis of Biodegradability

The ANOVA findings regarding the biodegradation of different pesticide formulations reveal that those derived from plants break down considerably more rapidly than their synthetic counterparts. The p-value falls beneath 0.05, affirming that the variations in biodegradation rates hold statistical significance. This indicates that environmentally conscious formulations exhibit greater sustainability, as they decompose swiftly in both terrestrial and aquatic environments. Conversely, artificial pesticides undergo a significantly more gradual breakdown, resulting in enduring remnants within the ecosystem. The results highlight that formulations derived from plants and nanoparticles are not only potent in managing pests but also present a reduced long-term ecological threat, underscoring the significance of embracing

eco-friendly chemistry approaches for sustainable farming practices.

The results underscore that environmentally sustainable pesticides, such as those derived from plants and solutions utilising silver nanoparticles, demonstrate comparable effectiveness to conventional synthetic pesticides, all the while delivering considerable ecological advantages. Their ability to break down naturally and reduced harm to non-target species, including helpful insects and soil microbes, renders them a compelling option for eco-friendly pest control. The statistical evaluations bolster the assertion that these formulations are not only efficient but also environmentally friendly. These findings support the ongoing advancement and implementation of Eco-friendly chemistry-derived pesticides as a strategy to diminish the ecological footprint of farming while ensuring the safeguarding of crops.

## DISCUSSION

The increasing demand for Eco-friendly farming methods has underscored the ecological and health hazards associated with traditional chemical pesticides. The growing apprehensions regarding pesticide remnants in our food supply, soil pollution, and the detrimental impacts on non-target species demand a transition to more Eco-friendly options. Sustainable chemistry presents an encouraging strategy for addressing these obstacles, as it emphasises reducing the ecological impact of chemical procedures and creating safer, compostable options. Within this framework, the advancement of environmentally sustainable pesticides utilising botanical extracts and nanotechnology signifies a groundbreaking approach.

Utilising botanical-based solutions has demonstrated significant potential in tackling pest management while remaining Eco-friendly. These compositions harness the inherent pesticidal characteristics of flora including *Ocimum* species, *Tectona grandis*, and *Acacia ehrenbergiana*, which are abundant in bioactive substances such as alkaloids, flavonoids, and terpenoids (Kashyap *et al.*, 2022; Alamier *et al.*, 2023). These substances demonstrate not just insecticidal and antimicrobial properties but also present a sustainable substitute for synthetic pesticides, which tend to linger in the ecosystem and build up within food chains (Rotti *et al.*, 2023). The outcomes of this research support these conclusions, as plant-derived

pesticides attained elevated pest mortality levels while remaining biodegradable and harmless to non-target species, including advantageous insects and soil microorganisms (Rai *et al.*, 2018; Giri *et al.*, 2022). This corresponds with the fundamental tenets of Eco-friendly chemistry, which seek to minimise the employment of dangerous materials while harnessing sustainable resources (Greene *et al.*, 2016). Moreover, nanotechnology has surfaced as a pivotal advancement in the creation of environmentally sustainable pesticides. Silver nanoparticles, especially those derived from botanical extracts, have exhibited remarkable antimicrobial and insecticidal capabilities (Alamier *et al.*, 2023; Giri *et al.*, 2022). The Eco-friendly production of nanoparticles presents numerous benefits, including diminished ecological harm and enhanced effectiveness in managing pests. Silver nanoparticles possess the remarkable ability to biodegrade, guaranteeing that they do not persist in the ecosystem. Their diminutive dimensions and expansive surface area facilitate precise release and focused effectiveness, thereby minimising the likelihood of pesticide resistance and harmful effects on non-target species (Khan *et al.*, 2020; Zhang *et al.*, 2024). The results of this research indicate that formulations utilising silver nanoparticles attained elevated pest mortality rates alongside advantageous biodegradability, thereby reinforcing the promise of nanotechnology in crafting Eco-friendly pest management strategies (Kashyap *et al.*, 2022; Rautela *et al.*, 2019). This is particularly significant considering the escalating worries regarding pesticide resistance, a situation that arises when pests adapt to withstand synthetic substances, diminishing their efficacy as time progresses (Muñoz *et al.*, 2023).

Although environmentally conscious pesticides are increasingly recognised as a more secure option, their extensive implementation encounters numerous obstacles. A significant obstacle lies in the financial viability and potential for expansion of Eco-friendly pesticides for extensive agricultural application (Arora & Mishra, 2023). Solutions rooted in green chemistry, such as botanical pesticides and nanomaterials, are frequently viewed as pricier than conventional chemical pesticides. Nonetheless, the enduring advantages of diminished ecological pollution and enhanced public well-being may counterbalance these upfront expenditures. Moreover, with the rising interest in Eco-friendly farming methods, the

benefits of scale and innovations in nanoparticle manufacturing may render environmentally friendly pesticides more financially feasible (Alex *et al.*, 2024). Moreover, backing from policy will be essential in surmounting these obstacles. It is essential for governmental entities and regulatory organisations to promote investigations into sustainable pesticides, simplify the approval procedures, and extend financial assistance to farmers who embrace these innovative practices (Osmani *et al.*, 2024; Milini *et al.*, 2019). Regarding ecological consequences, the adoption of eco-friendly pesticides represents a notable advancement in mitigating the detrimental impacts associated with conventional pesticides. Traditional synthetic substances are recognised for polluting soils, waterways, and the atmosphere, leading to extensive ecological disturbances and playing a role in the decline of biodiversity (Wang *et al.*, 2012; Lee *et al.*, 2021). According to the findings of this research, pesticides derived from plants and silver nanoparticles are environmentally friendly and decompose significantly faster than their artificial alternatives (Greene *et al.*, 2016). The ability to biodegrade diminishes the lasting presence of pesticides in the environment, consequently lowering the prolonged threat of ecological pollution and harm to ecosystems (Rai *et al.*, 2018). Additionally, these environmentally conscious formulations generally exhibit reduced toxicity towards non-target organisms, including pollinators and soil microbes, which play a crucial role in sustaining vibrant ecosystems and enhancing agricultural output (Giri *et al.*, 2022; Khan *et al.*, 2020). This represents an essential advantage, considering the detrimental impacts of artificial pesticides on ecological diversity and the alarming decrease in pollinator numbers globally (Zhu & Gao, 2008; Lee *et al.*, 2021).

The notable decrease in pesticide remnants found in food items treated with environmentally safe pesticides is yet another crucial factor to contemplate. Residues of pesticides present in food items can present significant health hazards to individuals, leading to ailments like cancer, neurological issues, and disruptions in hormonal balance (Zhu & Gao, 2008; Kong *et al.*, 2023). Transitioning to agrochemicals rooted in green chemistry can significantly reduce the likelihood of harmful residues, thereby enhancing food safety and promoting better public health results (Kashyap *et al.*, 2022). Biodegradable pesticides, specifically, guarantee that these substances do not build up within food chains, providing a more secure option for consumers. The

shift towards environmentally sustainable pesticides harmonises with the objectives set forth by the United Nations Sustainable Development Goals (SDGs), especially those concerning conscientious consumption and production (Alex *et al.*, 2024). Eco-friendly farming practices, propelled by the integration of environmentally conscious chemical methods, have the potential to mitigate adverse ecological effects associated with agriculture, all while preserving efficiency and safeguarding food availability (Arora & Mishra, 2023). The extensive adoption of these sustainable options has the potential to alleviate the worldwide issues brought about by climate change, ecological decline, and resistance to pesticides. Consequently, the ongoing advancement and acceptance of Eco-friendly pesticides not only bolster the aims of sustainable farming but also enhance wider environmental and health aspirations worldwide.

## CONCLUSION

The creation of sustainable pesticides via green chemistry presents an encouraging substitute for traditional synthetic substances, delivering considerable advantages for both the environment and public health. Formulations derived from plants and silver nanoparticles have shown remarkable effectiveness in managing pests, all while being environmentally friendly and safe for non-target species. These discoveries highlight the significance of Eco-friendly chemistry in advancing sustainable farming by providing efficient, safer, and more environmentally conscious pest control alternatives. The data evaluations and findings from this research support the ongoing advancement of Eco-friendly pesticides, which are not only efficient but also play a significant role in diminishing agricultural contamination and fostering a more sustainable Earth. Additional investigation into scalability, financial practicality, and regulatory backing will be crucial to enhance the accessibility and economic viability of these sustainable solutions for extensive agricultural operations.

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## Conflict of interest

The author declare that we have no conflict of interest.

## REFERENCES

1. Alamier, W. M.; Oteef, M. D. Y.; Bakry, A. M.; Hasan, N.; Ismail, K. S., & Awad, F. S., Green synthesis of silver nanoparticles using *Acacia ehrenbergiana* plant cortex extract for efficient removal of rhodamine B cationic dye from wastewater and the evaluation of antimicrobial activity., *ACS Omega.*, **2023**, *8*, 18901–14. <https://doi.org/10.1021/acsomega.3c01292>
2. Alex, A. M.; Subburaman, S.; Chauhan, S.; Ahuja, V.; Abdi, G., & Tarighat, M. A., Green synthesis of silver nanoparticle prepared with *Ocimum* species and assessment of anticancer potential., *Scientific Reports.*, **2024**, *14*, 11707. <https://doi.org/10.1038/s41598-024-61946-y>
3. Alsammarraie, F. K.; Wang, W.; Zhou, P.; Mustapha, A., & Lin, M., Green synthesis of silver nanoparticles using turmeric extracts and investigation of their antibacterial activities., *Colloids and Surfaces B: Biointerfaces.*, **2018**, *171*, 398–405. <https://doi.org/10.1016/j.colsurfb.2018.07.059>
4. Arora, N. K., & Mishra, I., Responsible consumption and production: A roadmap to sustainable development., *Environmental Sustainability.*, **2023**, *6*, 1–6. <https://doi.org/10.1007/s42398-023-00266-9>
5. Asif, M.; Yasmin, R.; Asif, R.; Ambreen, A.; Mustafa, M., & Umbreen, S., Green synthesis of silver nanoparticles (AgNPs), structural characterization, and their antibacterial potential., *Dose-Response.*, **2022**. <https://doi.org/10.1177/15593258221088709>
6. Bruna, T.; Maldonado-Bravo, F.; Jara, P., & Caro, N., Silver nanoparticles and their antibacterial applications., *International Journal of Molecular Sciences.*, **2021**, *22*, 7202. <https://doi.org/10.3390/ijms22137202>
7. Cong, L.; Zou, B.; Palacios, A.; Navarro, M. E.; Qiao, G., & Ding, Y., Thickening and gelling agents for formulation of thermal energy storage materials-a critical review., *Renewable and Sustainable Energy Reviews.*, **2022**, *155*, 111906. <https://doi.org/10.1016/j.rser.2021.111906>
8. Dhaka, A.; Mali, S. C.; Sharma, S., & Trivedi, R., A Review on biological synthesis of silver nanoparticles and their potential applications., *Results in Chemistry.*, **2023**, *6*, 101108. <https://doi.org/10.1016/j.rechem.2023.101108>
9. Giri, A. K.; Jena, B.; Biswal, B.; Pradhan, A. K.; Arakha, M.; Acharya, S.; Acharya, L., Green synthesis and characterization of silver nanoparticles using *Eugenia roxburghii* DC. extract and activity against biofilm-producing bacteria., *Scientific Reports.*, **2022**, <https://doi.org/10.1038/s41598-022-12484-y>
10. Greene, B. H. C.; Robertson, K. N.; Young, J. C. O. C., & Clyburne, J. A. C., Lactic acid demineralization of green crab (*Carcinus maenas*) shells: Effect of reaction conditions and isolation of an unusual calcium complex., *Green Chemistry Letters and Reviews.*, **2016**, *9*, 1–11. <https://doi.org/10.1080/17518253.2015.1119891>
11. Grison, C., & Ki, Y. L. T., Ecocatalysis, a new vision of green and sustainable chemistry., *Current Opinion in Green and Sustainable Chemistry.*, **2021**, *29*, 100461. <https://doi.org/10.1016/j.cogsc.2021.100461>
12. Hegde, A. R.; Kunder, M. U.; Narayanaswamy, M.; Murugesan, S.; Furtado, S. C.; Veerabhadraiah, B. B., & Srinivasan, B., Advancements in sunscreen formulations: Integrating polyphenolic nanocarriers and nanotechnology for enhanced UV protection., *Environmental Science and Pollution Research.*, **2024**, *31*, 38061–82. <https://doi.org/10.1007/s11356-024-33712-0>
13. Kashyap, N.; Kumari, A.; Raina, N.; Zakir, F.; & Gupta, M., Prospects of essential oil-loaded nanosystems for skincare., *Phytomed Plus.*, **2022**, *2*, 100198. <https://doi.org/10.1016/j.phyplu.2021.100198>
14. Khalil, K. A.; Fouad, H.; Elsarnagawy, T.; & Almajhdi, F. N., Preparation and characterization of electrospun PLGA/silver composite nanofibers for biomedical applications., *International Journal of Electrochemical Science.*, **2013**, *8*, 3483–93. [https://doi.org/10.1016/S1452-3981\(23\)14406-3](https://doi.org/10.1016/S1452-3981(23)14406-3)

15. Khan, S. A.; Shahid, S.; Shahid, B.; Fatima, U., Abbasi, S. A., Green synthesis of MnO nanoparticles using *Abutilon indicum* leaf extract for biological, photocatalytic, and adsorption activities., *Biomolecules.*, **2020**, *10*, 785. <https://doi.org/10.3390/biom10050785>
16. Khan, Y.; Sadia, H.; Shah, S. Z. A.; Khan, M. N.; Shah, A. A.; Ullah, N.; Ullah, M. F.; Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A Review. *Catalysts.*, **2022**, *12*, 1386. <https://doi.org/10.3390/catal12111386>
17. Kurul, F.; Turkmen, H.; Cetin, A. E., & Topkaya, S. N., Nanomedicine: How nanomaterials are transforming drug delivery, bio-imaging, and diagnosis., *Next Nanotechnology.*, **2025**, *7*, 100129. <https://doi.org/10.1016/j.nxnano.2024.100129>
18. Lee, T. C.; Anser, M. K.; Nassani, A. A.; Haffar, M.; Zaman, K.; Abro, M. M. Q., Managing natural resources through sustainable environmental actions: A cross-sectional study of 138 countries., *Sustainability.*, **2021**, *13*, 12475. <https://doi.org/10.3390/su132212475>.
19. Milin i, D. D.; Popovi, D. A.; Levi, S. M.; Kostić, A. Ž.; Tešić, Ž. L.; Nedović, V. A., & Pešić, M. B., Application of polyphenol-loaded nanoparticles in the food industry., *Nanomaterials.*, **2019**, *9*, 1629. <https://doi.org/10.3390/nano9111629>
20. Mishra, R.; Militky, J.; Baheti, V.; Huang, J.; Kale, B.; Venkataraman, M.; Bele, V.; Arumugam, V.; Zhu, G., Wang, Y., The production, characterization, and applications of nanoparticles in the textile industry., *Textile Progress.*, **2014**, *46*, 133–226. <https://doi.org/10.1080/00405167.2014.964474>
21. Mohajerani, A.; Burnett, L.; Smith, J. V.; Kurmus, H.; Milas, J.; Arulrajah, A.; Horpibulsuk, S.; Kadir, A. A., Nanoparticles in construction materials and other applications, and implications of nanoparticle use., *Materials.*, **2019**, *12*, 3052. <https://doi.org/10.3390/ma12193052>
22. Muñoz, F. L.; Meramo, S.; Ricardez-Sandoval, L.; Gonzalez, A. D.; Castillo, B. C.; Quiroga, A. G.; Baptiste, B. L. G.; León-Pulido, J. Insights from an exergy analysis of a green chemistry chitosan biorefinery., *Chemical Engineering Research and Design.*, **2023**, *194*, 666–77. <https://doi.org/10.1016/j.cherd.2023.04.038>
23. Osman A. I.; Zhang, Y.; Farghali, M.; Rashwan, A. K.; Eltaweil, A. S.; Abd, E. M.; El-Monaem, I. M. A.; Mohamed., Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A Review. *Environmental Chemistry Letters.*, **2024**, *22*, 841–87. <https://doi.org/10.1007/s10311-023-01682-3>
24. Rai, P. K.; Kumar, V.; Lee, S. S.; Raza, N.; Kim, K.-H.; Ok, Y. S., & Tsang, D. C. W. Nanoparticle-plant interaction: Implications in energy, environment, and agriculture., *Environmental International.*, **2018**, *119*, 1–19. <https://doi.org/10.1016/j.envint.2018.06.012>
25. Rashid, A. B., & Hoque, M. E., Polymer nanocomposites for defense applications., *In Advanced Polymer Nanocomposites.*, **2022**, 373–414). Elsevier. <https://doi.org/10.1016/B978-0-12-824492-0.00015-5>
26. Rautela, A.; Rani, J., & Debnath, M., Green synthesis of silver nanoparticles from *Tectona grandis* seeds extract: Characterization and mechanism of antimicrobial action on different microorganisms., *Journal of Analytical Science and Technology.*, **2019**. <https://doi.org/10.1186/s40543-018-0163-z>
27. Rotti, R. B.; Sunitha, D. V.; Manjunath, R.; Roy, A.; Mayegowda, S. B., Gnanaprakash, A. P., Alghamdi, S., Green synthesis of MgO nanoparticles and its antibacterial properties., *Frontiers in Chemistry.*, **2023**. <https://doi.org/10.3389/fchem.2023.1143614>
28. Sim, S., & Wong, N., Nanotechnology and its use in imaging and drug delivery (Review), *Biomedicine Reports.*, **2021**, *14*, 42. <https://doi.org/10.3892/br.2021.1418>
29. Sternberg, J.; Sequerth, O., & Pilla, S., Green chemistry design in polymers derived from lignin: Review and perspective., *Progress in Polymer Science.*, **2021**, *113*, 101344. <https://doi.org/10.1016/j.progpolymsci.2020.101344>

30. Volnyanska, O. V.; Mironyak, M. O.; Myrhorodska-Terentieva, V. D.; Avdienko, T. N., & Nikolenko, M. V., Development of a cosmetic product for the face based on hyaluronic acid and honey., *Voprosy Khimii i Khimicheskoi Tekhnologii.*, **2024**, *155*(4), 17–24. <https://doi.org/10.32434/0321-4095-2024-155-4-17-24>
31. Wang, G. D.; Mallet, F. P.; Ricard, F., & Heng, J.Y.Y., Pharmaceutical nanocrystals., *Current Opinion in Chemical Engineering.*, **2012**, *1*, 102–7. <https://doi.org/10.1016/j.coche.2011.12.001>
32. Zhang, Y.; Liu, F.; Zhang, J.; Gao, W.; Jian, Y., & Wang, L., Life cycle thinking-based greenness framework for advancing green chemistry: Case study with typical ionic liquids for cellulose dissolution and regeneration., *ACS Sustainable Chemistry & Engineering.*, **2024**, *12*, 6400–11. <https://doi.org/10.1021/acssuschemeng.4c00610>
33. Zhu, W., & Gao, J., The use of botanical extracts as topical skin-lightening agents for the improvement of skin pigmentation disorders., *Journal of Investigative Dermatology Symposium Proceedings.*, **2008**, *13*, 20–4. <https://doi.org/10.1038/jidsymp.2008.8>